

Anchoring the Universal Distance Scale via a Wesenheit Template

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ABSTRACT

A *VI* Wesenheit diagram featuring SX Phoenicis, δ Scuti, RR Lyrae, type II and classical Cepheid variables is calibrated by means of geometric-based distances inferred from HST, Hipparcos, and VLBA observations ($n = 30$). The distance to a target population follows from the offset between the observed Wesenheit magnitudes and the calibrated template. The method is evaluated by ascertaining the distance moduli for the LMC ($\mu_0 = 18.43 \pm 0.03(\sigma_{\bar{x}})$) and the globular clusters ω Cen, M54, M13, M3, and M15. The results agree with estimates cited in the literature, although a nearer distance to M13 is favoured (pending confirmation of the data's photometric zero-point) and observations of variables near the core of M15 suffer from photometric contamination. The calibrated LMC data is subsequently added to the Wesenheit template since that galaxy exhibits precise OGLE photometry for innumerable variables of differing classes, that includes recent observations for δ Scuti variables indicating the stars follow a steeper *VI* Wesenheit function than classical Cepheids pulsating in the fundamental mode. *VI* photometry for the calibrators is tabulated to facilitate further research, and includes new observations acquired via the AAVSO's robotic telescope network (e.g., VY Pyx: $\langle V \rangle = 7.25$ and $\langle V \rangle - \langle I \rangle = 0.67$). The approach outlined here supersedes the lead author's prior first-order effort to unify variables of the instability strip in order to establish reliable distances.

Subject headings:

1. Introduction

SX Phoenicis, δ Scuti, RR Lyrae, type II and classical Cepheid variables are useful for establishing distances to globular clusters, the Galactic center, and galaxies (McNamara et al. 2000, 2007; Kubiak & Udalski 2003; Pritzl et al. 2003; Matsunaga et al. 2006, 2009; Majaess et al. 2009a,b; Majaess 2009, 2010a,b). However, there is an absence of precise trigonometric parallaxes for nearby type II Cepheids and RR Lyrae variables which would otherwise serve to anchor the standard candles. RR Lyrae is the single mem-

ber of its class exhibiting a parallax uncertainty $\leq 30\%$ (Table 1). Likewise, κ Pav and VY Pyx are unique among type II Cepheids that feature marginal parallax uncertainties (Table 1). The meagre statistics presently hamper efforts to establish individual zero-points for each variable type, particularly given that the aforementioned calibrators may exhibit peculiarities or multiplicity, or may sample the edge of the instability strip. Variables on the hot edge of the instability strip are brighter relative to objects on the cool edge that share a common pulsation period. Ignoring the distribution of calibrators within the instabil-

ity strip may subsequently result in biased period- M_V and period-colour relations, especially in the absence of viable statistics (Turner 2010).

The aforementioned problems may be mitigated by adopting a holistic approach and calibrating a VI Wesenheit diagram featuring SX Phe, δ Scuti, RR Lyrae, type II and classical Cepheid variables. Wesenheit magnitudes are reddening-free and relatively insensitive to the width of the instability strip. The Wesenheit function is defined and discussed by Madore (1982), Opolski (1983, 1988), Madore & Freedman (1991, 2009), Kovács & Jurcsik (1997), Kovács & Walker (2001), Di Criscienzo et al. (2004, 2007), and Turner (2010).

In this study, a VI Wesenheit template characterizing differing variables of the instability strip is calibrated by means of geometric-based distances (§2.2) and the pertinent photometry (§2.1). The calibration is evaluated by establishing distances to the LMC, ω Cen, M54, M13, M3, and M15 (§2.3).

2. Analysis

2.1. Photometry (calibration)

The lead author has advocated that RR Lyrae variables and Cepheids obey VI -based Wesenheit and period-colour relations which are comparatively insensitive to metallicity (Udalski et al. 2001; Bono 2003; Pietrzyński et al. 2004; Majaess et al. 2008, 2009a,b; Bono et al. 2008; Majaess 2009, 2010a,b), hence the advantage of constructing such a relation. That conclusion is based in part upon a direct comparison of RR Lyrae variables, type II Cepheids, and classical Cepheids at common zero-points, which offers an opportunity to constrain the effects of chemical composition on their luminosities and intrinsic colours (Freedman & Madore 1996; Udalski et al. 2001; Dolphin et al. 2001; Majaess et al. 2009a,b; Majaess 2009, 2010a,b; Feast 2010, see also the historic precedent outlined in Tammann et al. 2008). For example, the distances inferred for the LMC, SMC, IC 1613, and several globular clusters from the aforementioned standard candles agree to within the uncertainties (Majaess et al. 2009b; Majaess 2009, 2010b), despite the neglect of metallicity corrections for variable types sampling different temperature, radius, and density regimes.

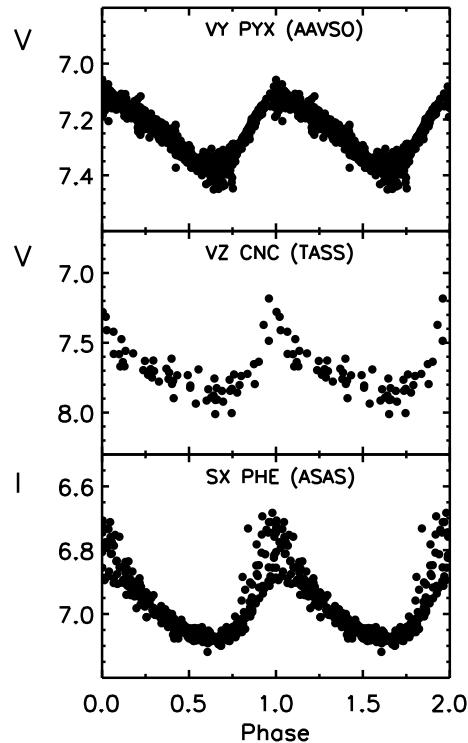


Fig. 1.— Light curves for a subsample of the objects studied here. Data for the type II Cepheid VY Pyx were obtained via the AAVSO’s robotic telescope network. An analysis of that photometry yields the following mean parameters for VY Pyx: $\langle V \rangle = 7.25$ and $\langle V \rangle - \langle I \rangle = 0.67$. VZ Cnc and SX Phe are multi-periodic, and thus the scatter exhibited is only tied in part to photometric uncertainties (Fig. 2).

Admittedly, the subject is actively debated (Smith 2004; Romaniello et al. 2008; Catelan 2009, and references therein). By contrast there appears to be a consensus that relations which rely on BV photometry are sensitive to variations in chemical abundance and a significant break in the period-magnitude relation is apparent (Majaess et al. 2009b, and references therein). Consequently, a VI -based Wesenheit calibration is developed here.

A notable success of the Hipparcos mission was the establishment of time-series and standardized photometry for bright stars. Hipparcos surveyed the sky in $B_T V_T$ while follow-up surveys such as ASAS and TASS obtained VI photometry (Pojmański 2002; Droege et al.

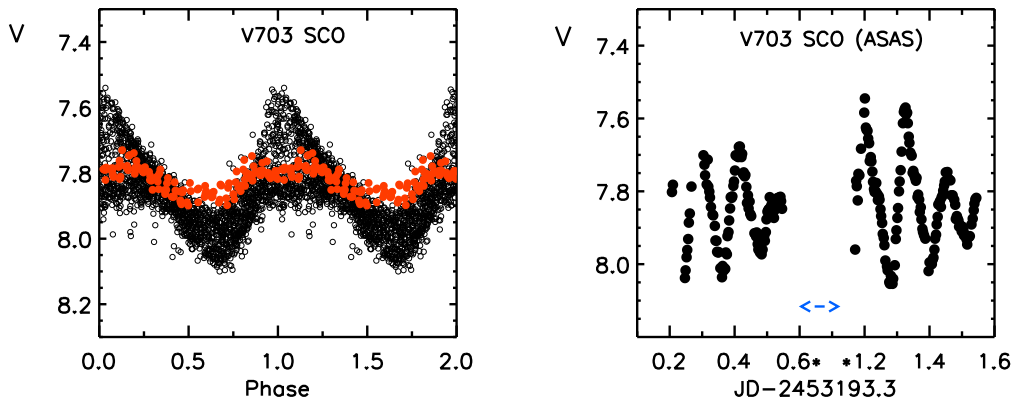


Fig. 2.— Several variables employed in the calibration (Table 1) are discernably multiperiodic and exhibit pronounced amplitude variations, as exemplified by observations of V703 Sco. Observations for V703 Sco were obtained via the AAVSO’s robotic telescope network (red dots) and ASAS. No prewhitening was performed.

2006). Observations from a series of studies by Balona & Stobie, in addition to data from the aforementioned sources, provide the photometry for the shorter period calibrators examined (Table 1). Additional observations for VY Pyx and V703 Sco were obtained via the AAVSO’s Sonoita (SRO) and Bright Star Monitor (BSM) telescopes.¹ The SRO features an SBIG STL-1001E CCD (fov: 20’x20’) mounted upon a 35-cm telescope stationed near the town of Sonoita, Arizona. The BSM features an SBIG ST8XME CCD (fov: 127’x84’) mounted upon a 6-cm wide-field telescope located at the Astrokolkhoz telescope facility near Cloudcroft, New Mexico. The AAVSO observations are tied to Landolt (1983, 1992) photometric standards according to precepts outlined in Henden & Kaitchuck (1990) (see also Henden & Munari 2008). The data for VZ Cnc were supplemented by observations taken at the Abbey Ridge Observatory (Lane 2007). VI photometry for Benedict et al. (2007) Galactic classical Cepheid calibrators was obtained from the catalogue of Berdnikov et al. (2000).

The phased light curves for several variables are presented in Fig. 1. The relevant photometry (is) shall be available online via databases maintained by CDS, ASAS, TASS, and the AAVSO. The pulsation periods employed to

phase the data were adopted from the GCVS (Samus et al. 2009a), the AAVSO’s VSX archive² (Watson, Henden & Price 2010), and the GEOS RR Lyr survey (Le Borgne et al. 2007). Several pulsators display pronounced amplitude variations and are discernably multiperiodic (e.g., AI Vel, V703 Sco, SX Phe, Figs. 1 and 2), topics that shall be elaborated upon elsewhere.

2.2. Parallaxes (calibration)

24 variables with parallaxes measured by Hipparcos and HST are employed to calibrate the VI Wesenheit diagram (Table 1). The sample consists of 8 SX Phoenicis and δ Scuti variables, 4 RR Lyrae variables, 2 type II Cepheids, and 10 classical Cepheids. That sample is supplemented by 6 type II Cepheids detected by Macri et al. (2006) in their comprehensive survey of the galaxy M106 (Majaess et al. 2009b), which features a precise geometric-based distance estimate (Herrnstein et al. 1999). It is perhaps ironic that stars 7.2 Mpc distant may be enlisted as calibrators because of an absence of viable parallaxes for nearby objects. Type II Cepheids within the inner region of M106 were not employed in the calibration because of the likelihood of photometric contamination via crowding and blending (Fig. 4, see also Stanek & Udalski 1999; Mochejska et al.

¹<http://www.aavso.org/aavsonet>

²<http://www.aavso.org/vsx/>

TABLE 1
POTENTIAL CALIBRATORS

Object	Variable Type	σ_{π}/π	Source	VI Photometry
SX Phe	SX Phe	0.04	van Leeuwen et al. 2007	ASAS
V703 Sco	δ Scuti:	0.12	van Leeuwen et al. 2007	Balona & Stobie 1983, AAVSO
AI Vel	δ Scuti:	0.03	van Leeuwen et al. 2007	Balona & Stobie 1980b, ASAS
VW Ari	SX Phe:	0.07	van Leeuwen et al. 2007	TASS
AD CMi	δ Scuti	0.24	van Leeuwen et al. 2007	Balona & Stobie 1983, TASS
VZ Cnc	δ Scuti	0.10	van Leeuwen et al. 2007	Balona & Stobie 1983, TASS, ARO
RS Gru	δ Scuti:	0.29	van Leeuwen et al. 2007	Balona & Martin 1978
V474 Mon	δ Scuti:	0.04	van Leeuwen et al. 2007	Balona & Stobie 1980a
RR Lyrae	RR Lyr	0.05	Benedict et al. 2002a	TASS
UV Oct	RR Lyr	0.33	van Leeuwen et al. 2007	ASAS
XZ Cyg	RR Lyr	0.37	van Leeuwen et al. 2007	TASS
BN Vul	RR Lyr	0.37	van Leeuwen et al. 2007	TASS
VY Pyx	TII Cep	0.09	van Leeuwen et al. 2007	AAVSO (this study)
κ Pav	TII Cep	0.12	van Leeuwen et al. 2007	Shobbrook 1992, Berdnikov et al. 2008
MSB2006 O-38462	TII Cep	0.05	Herrnstein et al. 1999	Macri et al. 2006
MSB2006 O-07822	TII Cep	0.05	Herrnstein et al. 1999	Macri et al. 2006
MSB2006 O-11134	TII Cep	0.05	Herrnstein et al. 1999	Macri et al. 2006
MSB2006 O-28609	TII Cep	0.05	Herrnstein et al. 1999	Macri et al. 2006
MSB2006 O-29582	TII Cep	0.05	Herrnstein et al. 1999	Macri et al. 2006
MSB2006 O-31291	TII Cep	0.05	Herrnstein et al. 1999	Macri et al. 2006
RT Aur	TI Cep	0.08	Benedict et al. 2007	Berdnikov et al. 2000
T Vul	TI Cep	0.12	Benedict et al. 2007	Berdnikov et al. 2000
FF Aql	TI Cep	0.06	Benedict et al. 2007	Berdnikov et al. 2000
δ Cep	TI Cep	0.04	Benedict et al. 2002b, 2007	Berdnikov et al. 2000
Y Sgr	TI Cep	0.14	Benedict et al. 2007	Berdnikov et al. 2000
X Sgr	TI Cep	0.06	Benedict et al. 2007	Berdnikov et al. 2000
W Sgr	TI Cep	0.09	Benedict et al. 2007	Berdnikov et al. 2000
β Dor	TI Cep	0.05	Benedict et al. 2007	Berdnikov et al. 2000
ζ Gem	TI Cep	0.06	Benedict et al. 2007	Berdnikov et al. 2000
ℓ Car	TI Cep	0.10	Benedict et al. 2007	Berdnikov et al. 2000

NOTE.—Unpublished *I*-band ASAS observations for several calibrators were kindly provided by G. Pojmański (<http://www.astro.uw.edu.pl/asas/>). ** There are concerns regarding the photometric zero-point for bright stars sampled in the all-sky surveys (Henden & Sallman 2007; Pojmański 2009). Colons next to the variable types indicate cases where contradictory designations were assigned in the literature. Distinguishing between population II SX Phe variables and population I δ Scuti variables on the basis of metallicity alone may be inept granted there are innumerable metal-rich RR Lyrae variables exhibiting $[\text{Fe}/\text{H}] \geq -0.5$ (e.g., Feast et al. 2008).

2000, 2001; Macri et al. 2006; Vilardell et al. 2007; Smith et al. 2007; Majaess et al. 2009b; Majaess 2010b). The stars employed were observed in the outer regions of M106 where the stellar density and surface brightness are diminished by comparison. Extragalactic type II Cepheids are often detected fortuitously near the limiting magnitude of surveys originally aimed at discovering more luminous classical Cepheids, hence the preference toward detecting the longer period (brighter) RV Tau subclass (Majaess et al. 2009b).

Parallaxes for several calibrators were sought from the van Leeuwen (2007) catalogue of revised Hipparcos data (Table 1). The parallaxes cited in the study differ from those issued by van Leeuwen et al. (2007). The reliability of Hipparcos parallaxes has been questioned because of disagreements over the distance to Polaris and the Pleiades cluster (Turner & Burke 2002; Soderblom et al. 2005; Turner et al. 2005; van Leeuwen et al. 2007; van Leeuwen 2009a,b; Turner 2009, 2010). The Hipparcos parallax for the Pleiades corresponds to a distance of $d = 120.2 \pm 1.9$ pc (van Leeuwen 2009a), whereas HST observations imply $d = 134.6 \pm 3.1$ pc (Soderblom et al. 2005). A comparison of stars with both Hipparcos and HST parallaxes indicates that there may be a marginal systemic offset ($\simeq 5\%$). However, the statistics are presently too poor. van Leeuwen (2009a,b) argues in favor of the Hipparcos scale and the reader is referred to that comprehensive study.

Tammann et al. (2008) questioned the reliability of HST parallaxes for nearby classical Cepheids since the resulting period-magnitude relations inferred from that sample do not match their own functions (Tammann et al. 2003; Sandage et al. 2004), which were constructed from the best available data at the time³ and prior to the publication of the HST parallaxes (Benedict et al. 2007). The viability of the HST parallaxes is supported by the results of Turner (2010) and Majaess (2010b). A central conclusion of Turner (2010) was that the classical Cepheid period-luminosity relation tied to the HST sample is in agreement with that inferred from cluster Cepheids. Majaess (2010b)

reaffirmed that the slope of the *VI* Wesenheit function inferred from Benedict et al. (2007) HST data matches that of precise ground-based observations of classical Cepheids in the LMC, NGC 6822, SMC, and IC 1613 (see Fig. 2 in Majaess 2010b). Classical Cepheids in the aforementioned galaxies span a sizeable abundance baseline and adhere to a common *VI* Wesenheit slope to within the uncertainties, thereby precluding a dependence on metallicity (see Fig. 2 in Majaess 2010b).

The uncertainty tied to the Wesenheit magnitude for a given calibrator is presently dominated by the parallax and distance uncertainties. Those uncertainties are converted into magnitude space (σ_w) via:

$$\begin{aligned}\sigma_w &\simeq |5 \log(d + \sigma_d) - 5 - (5 \log(d - \sigma_d) - 5)|/2 \\ &\simeq \left| 2.5 \log \left(\frac{d + \sigma_d}{d - \sigma_d} \right) \right| \\ &\simeq \left| 2.5 \log \left(\frac{\pi - \sigma_\pi}{\pi + \sigma_\pi} \right) \right|\end{aligned}$$

The uncertainty associated with the Wesenheit magnitudes for type II Cepheids in M106 (σ'_w) is estimated as:

$$\sigma'_w \simeq \sqrt{\sigma_{TII}^2 + \sigma_w^2}$$

Where σ_{TII} is the average photometric deviation of type II Cepheids occupying the outer region of M106 from the mean *VI* Wesenheit function.

The calibration derived here shall be bolstered by additional and precise parallax measurements. F. Benedict and coauthors are presently acquiring HST parallaxes for important stars such as κ Pav, XZ Cyg, UV Oct, and VY Pyx (Table 1).

2.3. Calibrated Wesenheit Diagrams

The calibrating and LMC *VI* Wesenheit diagrams are displayed in Fig. 3. The Wesenheit magnitudes were computed as follows:

$$\begin{aligned}W_{VI,0} &= \langle V \rangle - R_{VI}(\langle V \rangle - \langle I \rangle) - \mu_0 \\ W_{VI} &= \langle V \rangle - R_{VI}(\langle V \rangle - \langle I \rangle)\end{aligned}$$

Where $R_{VI} = 2.55$ is the canonical extinction law, although there are concerns with adopting a colour-independent extinction law. The Wesenheit magnitudes tied to BN Vul and AD CMi are spurious so the stars were omitted from Fig. 3.

³Turner (2010) has since revised the parameters for longer-period classical Cepheid calibrators, although continued work is needed and ongoing (survey initiated at the OMM, Artigau et al. 2010).

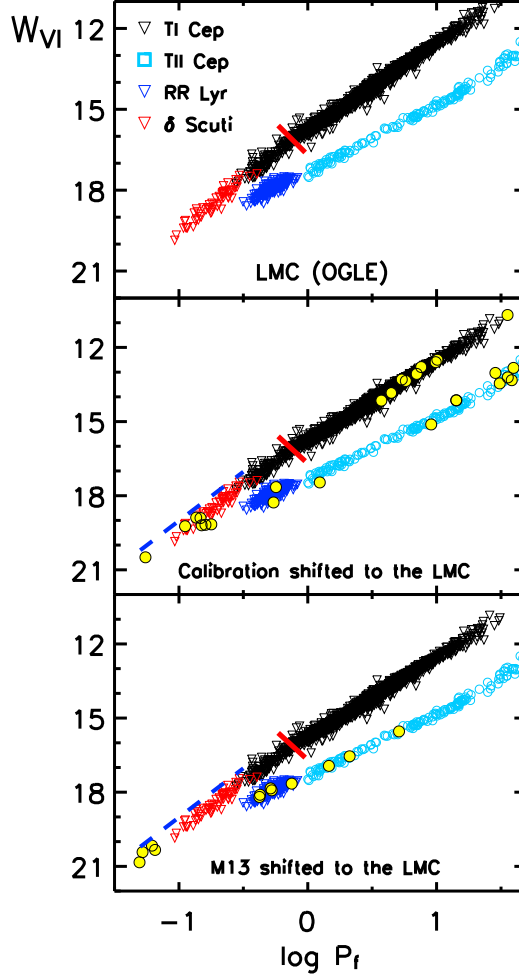


Fig. 3.— A *VI* Wesenheit diagram characterizing a subsample of the examined data. The distance to the LMC is secured by evaluating the offset from the calibration (*middle panel*, yellow dots, the size of the datapoints is representative of the uncertainties). The Wesenheit magnitudes of variable stars in globular clusters (e.g., M13, *bottom panel*, yellow dots) may be compared to the LMC template to derive the zero-point. The blue dashed line indicates the position of uncorrected δ Scuti stars pulsating in the overtone (see Poleski et al. 2010). A break in the classical Cepheid relation near $\log P_f \simeq -0.15$ may define the δ Sct / Cep boundary (see also Fig. 6 in Soszyński et al. 2008b, $\log P \simeq -0.3$).

The cases may be analogous to RT Aur, Y Sgr, or perhaps FF Aql (see Table 1 in van Leeuwen et al. 2007). RR Lyrae variables pulsating in the overtone were shifted by $\log P_f \simeq \log P_o + 0.13$ to yield the equivalent fundamental mode period (Walker & Nemec 1996; Hurdis & Krajci 2010). Fig. 3 was plotted with the fundamentalized periods so to illustrate the general continuity across

the variable types, however, plotting the uncorrected principal period is preferred so to permit a direct assessment of the pulsation mode.

The distance to a target population follows from the offset between the observed Wesenheit magnitudes and the calibration.

2.3.1. LMC

The resulting distance modulus for the LMC is $\mu_0 = 18.43 \pm 0.03(\sigma_{\bar{x}}) \pm 0.17(\sigma)$. That agrees with the value obtained by Majaess et al. (2008) and Majaess (2009), and exhibits smaller uncertainties. Likewise, the estimate is consistent with a mean derived from the NASA/IPAC Extragalactic Database (NED-D) master list of galaxy distances, which features over 300 distances for the LMC (Madore & Steer 2007; Steer & Madore 2010).^{4,5} The author's prior estimates were inferred by applying a *VI* Galactic classical Cepheid calibration (Majaess et al. 2008) to the LMC photometry of Udalski et al. (1999) and Sebo et al. (2002). Majaess et al. (2008) calibration is based primarily on the efforts of fellow researchers who established classical Cepheids as members of Galactic open clusters (e.g., Sandage 1958; Madore & van den Bergh 1975; Turner 2010) and secured precise trigonometric parallaxes (HST, Benedict et al. 2002b, 2007).

The latest OGLE LMC observations indicate that δ Scuti stars exhibit a steeper *VI* Wesenheit slope than classical Cepheids pulsating in the fundamental mode (Fig. 3, see also Soszyński et al. 2008b; Poleski et al. 2010). The pulsation modes of δ Scuti variables may be constrained by overlaying a target demographic—along with RR Lyrae and type II Cepheid variables which are often detected in tandem—upon the calibrated LMC Wesenheit template. SX Phe variables appear toward the shorter-period extension of the δ Scuti regime on the Wesenheit diagram (Fig. 3).

2.3.2. M3

The distance to variable stars in globular clusters may be established by comparing the observed Wesenheit magnitudes to the calibrated LMC template, which exhibits extensive statistics and period coverage for innumerable variable types. The distance modulus for M3 from the analysis is: $\mu_0 = 15.12 \pm 0.01(\sigma_{\bar{x}}) \pm 0.20(\sigma)$. That agrees with Harris (1996) estimate of $\mu_0 \simeq 15.08$. Harris (1996) distances to globular clusters are established from the magnitude of the horizontal

branch.⁶

2.3.3. ω Cen

The distance modulus for ω Cen from the aforementioned approach is: $\mu_0 = 13.49 \pm 0.01(\sigma_{\bar{x}}) \pm 0.09(\sigma)$. Estimates in the literature for ω Cen span a range: $\mu_0 \simeq 13.41 \rightarrow 13.76$ (van de Ven et al. 2006; Del Principe et al. 2006). The *VI* photometry characterizing variables in ω Cen was obtained somewhat indirectly (see Weldrake et al. 2007). Securing multiepoch *I*-band observations is therefore desirable to permit a more confident determination of the zero-point, and enable further constraints on the effects of chemical composition on the luminosities of RR Lyrae variables. Stars in ω Cen exhibit a sizeable spread in metallicity at a common zero-point owing to the presence of multiple populations ($-1.0 \geq [Fe/H] \geq -2.4$, Rey et al. 2000). Evaluating the correlation between the distance modulus computed for a given RR Lyrae variable and its abundance yields direct constraints on the effects of metallicity (e.g., Majaess 2009).

2.3.4. M13

An analysis of the variable stars in M13 yields: $\mu_0 = 14.09 \pm 0.02(\sigma_{\bar{x}}) \pm 0.06(\sigma)$ (caution warranted, see below). That may agree with the infrared weighted solution of $\mu_0 = 14.25$ by Buckley & Longmore (1992), but the estimate is significantly smaller than the distance modulus for M13 cited by Harris (1996) ($\mu_0 \simeq 14.43$). The observations of M13 are from a series of studies that detected at least 4 SX Phe variables, 5 RR Lyrae variables (4 RRc and 1 RRab), and 3 type II Cepheids (Kopacki et al. 2003; Pietrukowicz & Kaluzny 2004; Kopacki 2005). The surveys were conducted as part of renewed efforts to secure multi-band photometric parameters for variable stars in globular clusters (Pietrukowicz & Kaluzny 2003; Pietrukowicz et al. 2008, see also Sawyer 1939, Clement et al. 2001, Samus et al. 2009b).

Applying the *VI* RR Lyrae variable period-reddening calibration of Majaess (2010a) to the M13 data yields a mean colour excess of: $E_{B-V} = 0.06 \pm 0.02(\sigma)$ (caution warranted, see below). The

⁴<http://nedwww.ipac.caltech.edu/level5/NED1D/intro.html>

⁵<http://nedwww.ipac.caltech.edu/Library/Distances/>

⁶<http://physwww.mcmaster.ca/~harris/mwgc.ref>

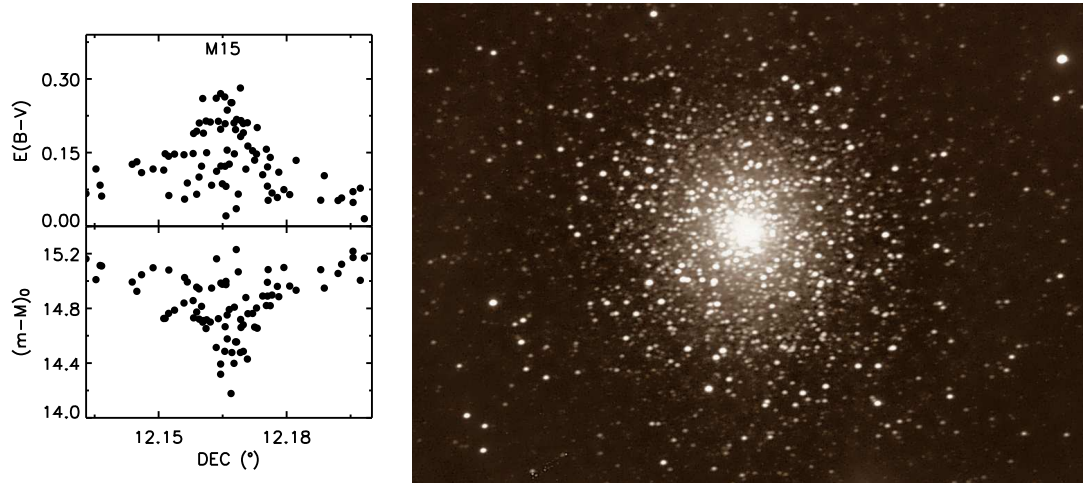


Fig. 4.— Variables near the core of M15 suffer from photometric contamination. The surface brightness and stellar density increase rapidly toward the core, thereby increasing the likelihood of contamination. *Left*, the distance moduli and colour excess for RR Lyrae variables are computed via the calibrations of Majaess et al. 2009a and Majaess 2010a. *Right*, M15 imaged from the ARO (Lane 2007). M15 is crucial since it is among the most metal-poor Galactic clusters and hosts a planetary nebula (Jacoby et al. 1997; Alves et al. 2000; Turner et al. 2010).

VI RR Lyrae variable period-colour relation derived by Pejcha & Stanek (2009) yields $E_{V-I} = 0.05 \pm 0.02(\sigma)$ ($E_{B-V} \simeq 0.04$). The estimates are larger than the reddening inferred from the NED extinction calculator for the direction toward M13 ($E_{B-V} \simeq 0.02$). The consensus position is that the line of sight toward M13 is unobscured, however the Wesenheit approach is extinction free and independent of that assertion (for the canonical extinction law). Applying the new reddening to previous optical estimates of the cluster’s distance modulus would result in a correction of $\Delta\mu_0 \simeq -E_{B-V} \times R_V \simeq -0.15$ (R_V , Turner 1976), thereby bringing the estimates into closer agreement.

The data for M13 are based on ground and HST photometry, which are challenging to standardize and may therefore be susceptible to a host of concerns related to photometric contamination and floating photometric zero-points (e.g., see Saha et al. 2006). If the photometry is trustworthy, then the distance and reddening estimates obtained for M13 are reliable. Additional observations are presently being acquired to facilitate that assessment.

2.3.5. M54

The distance modulus derived for M54 is $\mu_0 = 17.04 \pm 0.01(\sigma_{\bar{x}}) \pm 0.05(\sigma)$. That agrees with Harris (1996) estimate of $\mu_0 \simeq 17.14$.

2.3.6. M15

The distance modulus for M15 from the analysis is: $\mu_0 \geq 14.82$. Estimates in the literature for M15 span a range: $\mu_0 \simeq 14.69 \rightarrow 14.99$ (Arellano Ferro et al. 2006; McNamara et al. 2004). Applying the VI RR Lyrae variable period-reddening calibration of Majaess (2010a) yields a mean colour excess of $E_{B-V} < 0.12$, matching that cited by Harris (1996). However, the observations suffer from photometric contamination, particularly for stars near the cluster’s core where the surface brightness and stellar density increase rapidly (Fig. 4). Blending may introduce spurious flux and cause variables to appear brighter (often redder) and hence nearer (Fig. 4). Photometric contamination provides a viable explanation for the discrepancy noted in the Bailey diagram describing variables in M15 (see Corwin et al. 2008).

That contamination was overlooked by the lead author when previously investigating the cluster (Majaess 2009). Other globular cluster pho-

tometry should be examined in similar fashion pending the availability of published positional data beyond pixel coordinates. Photometric contamination may bias efforts to construct an RR Lyrae variable period-amplitude-metallicity relation, and may exaggerate the perceived spread of the cluster’s main-sequence and red giant branch, thereby mimicking the signature of multiple populations (in certain instances). A trend similar to that displayed in Fig. 4 is observed in data for extragalactic Cepheids (Majaess et al. 2009b). In an effort to constrain the effect of chemical composition on the luminosities of classical Cepheids, researchers have endeavored to compare the distance offset between classical Cepheids located in the central (metal-rich) and outer (metal-poor) regions of a particular galaxy (e.g., M101, M106, M33). A degeneracy complicates the analysis (photometric contamination) since the stellar density and surface brightness often increase toward the central region. Depending on the circumstances the effects of metallicity and blending/crowding may act in the same sense and be of similar magnitude (e.g., compare Figs. 17 and 18 in Macri et al. 2006, see also Macri et al. 2001). Furthermore, R (the ratio of total to selective extinction) may also vary as a function of radial distance from the centers of galaxies in tandem with the metallicity gradient. For example, the extinction law characterizing dust properties near the center of the Milky Way is possibly anomalous (Udalski 2003, see Kunder et al. 2008 for the dissenting view). As stated earlier, the author has advocated that VI -based Cepheid and RR Lyrae variable Wesenheit and period-colour relations are comparatively insensitive to metallicity, and thus the offset arises from photometric contamination or another source.

The uncertainties associated with the derived distance modulus and mean colour excess for M15 cited above are exacerbated systemically and statistically by the aforementioned bias (Fig. 4). The distance modulus and colour excess representing stars near the periphery of the cluster, where the effects of photometric contamination are mitigated, are: $\mu_0 \simeq 15$ and $E_{B-V} \simeq 0.06$ (Fig. 4). The analysis reaffirms the advantage of adopting a period-magnitude-colour approach to investigating RR Lyrae variables, in addition to the approach outlined in Fig. 3 or the canonical

$[\text{Fe}/\text{H}]-M_V$ relation. The slope of the Wesenheit function is also an important diagnostic for assessing photometric irregularities (Majaess et al. 2009b; Majaess 2010b), and should be assessed in tandem with the establishment of distances via the Wesenheit template (Fig. 3).

3. Summary and Future Research

A VI Wesenheit diagram unifying variables of the instability strip is calibrated by means of geometric-based distances inferred from HST, Hipparcos, and VLBA observations (Table 1, Fig. 3). The distance modulus for a target population is determined by evaluating the offset between the observed Wesenheit magnitudes and a calibrated template. The approach mitigates the uncertainties tied to establishing a distance scale based on type II Cepheids or RR Lyrae variables individually, since presently there is an absence of viable parallaxes. F. Benedict and coauthors are engaged in ongoing efforts to secure precise parallaxes for a host of variables employed in the calibration (Table 1).

To first order the distance moduli established for the LMC, ω Cen, M54, M13, M3, and M15 via the calibration agree with estimates in the literature (§2.3). VI photometry for variable stars in the globular clusters examined (and LMC) were sought from innumerable sources (Udalski et al. 1999; Layden & Sarajedini 2000; Soszyński et al. 2003, 2008,b, 2009; Kopacki et al. 2003; Pietrukowicz & Kaluzny 2004; Kopacki 2005; Benkő et al. 2006; Weldrake et al. 2007; Corwin et al. 2008; Poleski et al. 2010).

VI photometry for the calibrating set was acquired from the AAVSO’s robotic telescope network and other sources (Table 1, §2.1). This study reaffirms the importance of modest telescopes in conducting pertinent research (Percy 1986, 2007; Welch et al. 1995; Szabados 2003; Henden 2006; Paczyński 2006; Genet et al. 2009; Pojmański 2009; Udalski 2009; Turner et al. 2009a), whether that is facilitating an understanding of terrestrial mass extinction events, discovering distant supernovae, aiding the search for life by detecting exoplanets, or anchoring the universal distance scale (e.g., Price et al. 2005; Lane & Gray 2005; Charbonneau et al. 2009; Majaess et al. 2009c).

Lastly, the present holistic approach supersedes

the lead author’s prior first order and somewhat erroneous effort (Majaess 2009).⁷ Yet it is envisioned that the universal distance scale could be further constrained via the current approach by relying on an additional suite of calibrators, namely: variables in globular clusters that possess dynamically-established distances (e.g., ω Cen and M15, McNamara et al. 2004; van de Ven et al. 2006); δ Scuti stars in nearby open clusters (e.g., Pleiades, Praesepae, Hyades; Li & Michel 1999); variable stars in clusters with distances secured by means of eclipsing binaries (e.g., Cluster AgeS Experiment); and variables in the Galactic bulge that are tied to a precise geometric-based distance (Eisenhauer et al. 2005; Reid et al. 2009, bolstered by observations from the upcoming VVV survey; Minniti et al. 2010). The resulting *VI* Wesenheit calibration (Fig. 3) could be applied to galaxies beyond the LMC, such as the SMC (Udalski et al. 1999; Soszyński et al. 2002), IC 1613 (Udalski et al. 2001; Dolphin et al. 2001), and M33 (Sarajedini et al. 2006; Scowcroft et al. 2009), which feature *VI* observations for population I and II variables. The results of such an analysis would support ongoing efforts to constrain the Hubble constant (e.g., Ngeow & Kanbur 2006; Macri & Riess 2009). However, a successful outcome is contingent upon the admittedly challenging task of obtaining precise, commonly standardized, multiepoch, multiband, comparatively uncontaminated photometry.

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⁷SX Phe, RR Lyrae, and type II Cepheid variables may be characterized by a common *VI* Wesenheit function to *first order*, as noted by Majaess (2009, 2010a), but not to second order (Fig. 3).

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